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CURRENT SENSOR ARRANGEMENT WITH

TEST CURRENT GENERATOR

Field of the Invention

5 This invention relates to current  
sensor arrangements, and more particularly to  
current sensor arrangements which use magnetic  
sensing devices which may be, or are, subject  
to unit-to-unit variation as a result of  
manufacturing tolerances, and/or which, once  
10 manufactured, may be subject to errors or  
deviations as a result of temperature  
variations, aging, and the like.

Background of the Invention

15 Seagoing vessels, regardless of  
whether they are intended for sport, commerce,  
or warfare, share in common the need to  
maintain their buoyancy and control in the face  
of potentially violent conditions including  
storms, grounding, and/or hostile action.  
20 Maintaining control and buoyancy in the face of  
damage due to such violent conditions may  
require rapid amelioration of, or adaptation  
to, such damage. In a large ship, there may be

many compartments, the entrances to which are separated by a sufficient distance from each other so that considerable time may be required for movement from one compartment to another.

5 The existence of such compartments has in the past given rise to the need for an observer assigned to each compartment or set of compartments to monitor conditions. It might be thought that speaker tubes or telephones

10 would be suitable for communicating between each of the various compartments and a control center or bridge, but there is a real possibility that damage to a compartment might also damage the communications equipment.

15 Consequently, warships assign crew members to be messengers, whose duty is to carry information from the compartments to the control center or bridge in the event of a break in the communications. Damage to one

20 compartment of a ship may require adjustments in many compartments, as for example when flooding of a compartment requires redistribution of the ship's load or supplies to prevent excessive list. The adjustments may

25 include operation of valves and switches within the compartments, as might be required, for example, to start pumps and open valves for the dumping overboard of bilge water, or for redistributing liquid fuel from tanks on one

30 side of the ship to tanks on the other side. Because time is very important when attempting to cope with damage, warships have in the past

stationed crews at various locations about the ship. These crews are charged with the duties of operating valves and switches as commanded or trained. In addition to such adjustments, additional crews must be provided to be on standby for firefighting, for damage repair, and for tending the injured. In the case of a warship, a portion of the crew must additionally be used for manning weapons and countermeasure. Since the tending of injured presupposes that some of the crew is not capable of performing its duties, the crew must, even when reduced in number by casualties, be large enough to be able to perform all of the tasks associated with tending a ship in distress. All of these considerations result in the manning of ships with crews large enough to provide "surge" capability for the handling of any emergency. A large battleship of WWII vintage had a crew in excess of 3000 men, and an aircraft carrier in the vicinity of 5000. Even modern missile destroyers require crews exceeding 300 persons.

The presence of such large crews inevitably has its effects on ship design. It will be clear that the housekeeping and support requirements tend to expand disproportionately as the crew grows larger. The ship itself must be large in order to hold the oversize crew, and must carry additional stores such as food, which makes it larger still. Food preparation areas must be larger with a large crew, and the

additional food preparation personnel in turn  
require their own support staff and ship  
facilities. The cost of ships is adversely  
affected by the need for a crew of a size to  
5 provide surge capability, and the cost of  
operating such ships is directly increased by  
the supernumerary members of the crew. The  
operating cost is further increased by the need  
to maintain the supernumerary members. It is  
10 thus of great importance in ship design to take  
into account the staffing requirements of the  
ship, and to improve ship design in such a  
manner as to minimize the crew size.

The Navy has recognized the  
15 disadvantages of such large crews, and is  
examining ways in which automation might reduce  
crew sizes. In some proposed systems,  
automation controls valves, electrical motors,  
and the like by way of a reliable local area  
20 network. "Smart" controls coupled to the local  
area network monitor the status of the various  
components of the ship, make relatively  
autonomous decisions as to the actions to be  
taken in response to various sensed conditions  
25 in view of the state of ship readiness which an  
operator sets, and implements the decisions by  
operating various valves and equipments. Many  
of the equipments are electrically operated,  
such as ship drive, gun slewing mechanisms,  
30 weapon hatches, fuel pumps, and other motor-  
driven devices. It is desirable to monitor the  
electrical load current of such motor-driven

devices to aid in determining the state of the device itself, and also to determine that the commands are being carried out. Load current may be monitored by means of electrical current sensors.

Improved current sensors are desired.

Summary of the Invention

A current sensor arrangement for measuring a subject electrical current flow includes an elongated conductor having fixed dimensions, which is to stay invariant with time. The elongated conductor is configured for producing a generally planar magnetic field within a spatial region adjacent the conductor when the subject electrical current flows through the elongated conductor. A magnetic field sensing or measuring device is located in the spatial region with a particular direction generally parallel to the planar magnetic field. The magnetic field sensing device produces a signal voltage in response to a magnetic field in the particular direction therethrough, and the magnitude of the signal voltage is approximately linearly related to the magnitude of the magnetic field in its vicinity, at least over a limited range of magnetic fields. The magnetic field sensing device may be either temperature-dependent, variable in its sensitivity from device to device, or both, or neither. The magnetic field sensing device produces a magnetic-field-representative signal voltage in response to

the magnetic field. The current sensor arrangement also includes a controllable test or bias current generator magnetically coupled to the spatial region, for, when energized, generating a test current flow, which may be a predetermined current flow, for generating a test or bias magnetic field component in the spatial region. The test magnetic field component is desirably generally parallel with the planar magnetic field, whereby, or as a result of which, the magnetic field sensing device produces a magnetic-field-representative signal voltage related to the magnitude of the sum of the subject electric current with the test current. A control arrangement is coupled to the magnetic field sensing device and to the test current generating means, for recurrently energizing the controllable test current generating means, and for determining the magnitude of the current flow in the elongated conductor from at least (a) the magnitude of the magnetic-field-representative signal voltage during those times during which the controllable test current generating means is energized, (b) the magnitude of the magnetic-field-representative signal voltage during times in which the controllable test current generating means is not energized, and (c) the magnitude of the test current.

In a particular manifestation of the invention, the recurrent energization is periodic. Among the magnetic field sensing

devices for which the invention is usable are  
giant magnetoresistive device and spin-  
dependent tunneling devices. In one distinct  
version of the invention, the test current  
5 generator is galvanically coupled to the  
elongated conductor adjacent the spatial  
region, for causing the test current to flow  
through the elongated conductor and thereby  
generate the test magnetic field within the  
10 spatial region. In this distinct version, the  
control arrangement comprises a switching  
arrangement, for, when in the conducting state,  
gating the predetermined current to the  
elongated conductor, and for, when in the  
15 nonconducting state, preventing the  
predetermined current from flowing in the  
elongated conductor. The galvanic connections  
may be made by current conductors connected to  
the elongated conductor on either side of the  
20 spatial region.

In another distinct version of the  
current sensor arrangement according to the  
invention, the controllable test current  
generator comprises a second electrical  
25 conductor extending through the spatial region,  
electrically isolated from the elongated  
conductor, and preferably parallel therewith.  
In this other distinct version, the control  
arrangement includes a switching arrangement,  
30 for, when in the conducting state, gating the  
test or predetermined current to the second  
electrical conductor, and for, when in the

nonconducting state, preventing the test or predetermined current from flowing in the second electrical conductor.

Brief Description of the Drawing

5           FIGURE 1a is a simplified perspective or isometric view of a portion of an elongated electrical conductor through which a current to be measured flows, showing the magnetic field structure, and FIGURE 1b is a cross-sectional  
10           view of the conductor looking in direction 1b-1b, showing that the magnetic field is roughly planar in a region around the conductor;

15           FIGURE 2a is a simplified perspective or isometric view of a portion of a current sensor arrangement according to an aspect of the invention, which includes a portion of the conductor of FIGURE 1a, and FIGURE 2b is a cross-sectional view thereof looking in  
20           direction 2b-2b;

20           FIGURE 3 is a plot of average voltage/magnetic field performance of a Giant Magneto Resistive device;

25           FIGURE 4a is a simplified schematic diagram of a magnetic field sensing or measuring device associated with a subject-current carrying conductor and a test current generator which causes test current to flow in the same conductor with the subject current, and FIGURE 4b illustrates a variant thereof;

30           FIGURE 5a is a simplified diagram in block and schematic form of a current sensor arrangement according to an aspect of the



invention, illustrating one method for switching a test circuit generator ON and OFF, and FIGURE 5b illustrates an alternative version thereof;

5           FIGURE 6a is a simplified diagram in block and schematic form of a current sensor arrangement according to another aspect of the invention, in which the test current flows through a second path, independent of the path  
10           in which the current being measured flows, and FIGURE 6b illustrates an alternative version thereof;

15           FIGURES 7a and 7b are simplified perspective and cross-sectional views of a current sensor arrangement according to an aspect of the invention which is arranged for printed-circuit type fabrication, and which uses field concentrators;

20           FIGURE 8 is a diagram of sensed output voltage versus the sum of the currents in the spatial region of a GMR magnetic field sensor; and

25           FIGURE 9 is a simplified diagram in block and schematic form of a controller according to an aspect of the invention.

Description of the Invention

          A portion of an elongated conductor 10 is illustrated. Conductor 10 is not circular, but is instead generally flattened to  
30           define a pair of mutually parallel broad surfaces 10u, 10l and a pair of mutually parallel narrow surfaces 10ls and 10rs.

Conductors so shaped are commonly the result of fabrication of printed circuit traces. The conductor carries an unknown or subject current I which is to be measured. Current I of FIGURE 1a causes a magnetic field illustrated by field lines designated 12. A theoretical bisector designated 13 extends through the broad surfaces, roughly orthogonal to those broad surfaces. Reference to FIGURE 1b allows the general configuration of the magnetic field lines to be visualized as including a generally "flat" or planar portion or region 14 near the bisector 13. More particularly, field lines 12<sub>1</sub>, 12<sub>2</sub>, 12<sub>3</sub>, and 12<sub>4</sub> can be seen to be substantially straight and mutually parallel, thereby defining two planes extending back into the FIGURE. Thus, flow of the unknown or subject current to be measured results in a (actually two) generally planar magnetic field components near the bisector of the conductor.

FIGURE 2a illustrates elongated conductor 10 associated with a magnetic field sensing or measuring device 20, which can be held in place by any desired means, such as adhesive 26. Magnetic field sensing device 20 senses magnetic fields roughly within planar-magnetic-field spatial region 14, the general location of which is suggested by the region enclosed by the dash lines 14 in FIGURE 2b. The magnetic field sensing device 20 is illustrated as a featureless cylinder, as its shape is irrelevant. Magnetic field sensing

device 20 may be of any one of a number of types, including Giant Magneto-Resistive (GMR) devices or Spin Dependent Tunneling (SDT) devices. These devices are relatively small, and lend themselves to packaging in integrated-circuit chip carriers. Thus, the shape of the carrier is not particularly relevant to the operation.

It should be noted that at least some of the magnetic field sensing devices 20 which may be used in current sensor arrangements according to some aspects of the invention are preferentially sensitive to magnetic fields flowing in a particular direction therethrough.

The different types are variously known as "perpendicular" or "orthogonal" in which the maximum sensitivity is to magnetic field lines transverse to the plane of the device, and "lateral" in which maximum sensitivity is to magnetic fields lying parallel to the plane of the device. This need not concern us, since the magnetic field sensing device 20 of FIGURES 2a and 2b can always be mounted in an orientation relative to the magnetic field in the planar region 14 which maximizes its sensitivity, depending upon its characteristics. The magnetic field sensing device 20 may require energization, which can be provided from an external source by wires, one of which is illustrated as 22. In any case, the magnetic field sensing device 20 produces a sensed voltage which, within a

linear range, is roughly proportional to the magnetic field in its vicinity. This voltage can be take from the magnetic field sensing device 20 by means of wires, one of which is  
5 illustrated as 24, for use by a utilization device.

FIGURE 3 illustrates a plot 310 illustrating typical output voltage versus magnetic field strength for a Giant Magneto-  
10 Resistive device. It will be noted that the plot is quite straight in the region ranging from zero field to about 25 Oersteds. If this portion of the plot is used to make measurements, there is a substantial  
15 correspondence or correlation between the sensed voltage and the magnetic field in the vicinity 14 of the magnetic sensing device 20 of FIGURE 2b. Unfortunately, the GMR sensors vary substantially from unit to unit, so the  
20 voltage reading produced by a randomly selected GMR cannot be relied upon to provide an accurate indication of magnetic field strength.

Even if the GMR is selected to have response close to that of plot 310, it will be found  
25 that the response varies as a function of GMR temperature, so that even selection of the GMR cannot provide a reliably accurate indication of the magnetic field in the vicinity of the magnetic sensing device, and therefore also  
30 cannot provide a reliably accurate indication of the current in conductor 10 of FIGURES 2a and 2b. A selection process is expensive, and

would result in a costly current sensor arrangement. Very costly sensors would militate against their widespread use in a shipboard environment (or in any other  
5 environment, for that matter), which would tend to limit their usefulness in replacing human observations or readings, contrary to the desired reduction in ship crew requirements.

According to an aspect of the  
10 invention, each current sensor arrangement is "continually" or recurrently normalized, compensated, or tested, so that its sensitivity is known at, or near, the moment in time at which the measurement is made. In short, this  
15 is accomplished by generating a "known" test or bias magnetic field component within the spatial region in which the magnetic sensing device lies, and processing the resulting information together with information obtained  
20 during non-test times, to determine the magnitude of the subject current flowing through the elongated conductor. More particularly, as illustrated by the current sensor arrangement 400 in the simplified  
25 schematic diagram of FIGURE 4a, a test or bias current generating circuit designated generally as 410 includes a "current" source designated generally as 412, which includes a voltage source illustrated as a battery 414 and two  
30 resistors, namely resistors 416 and 418. Those skilled in the art know that a voltage source produces voltage and, when connected in a

circuit, also produces current. In order to isolate the voltage source 414 from the conductor 10, the connections of voltage source 414 to conductor 10 are made by way of  
5 resistors 416 and 418. More particularly, resistor 416 connects the negative terminal of voltage source 414 to conductor 10 "downstream" (relative to the direction of current flow in conductor 10) from planar-magnetic-field region  
10 14, and resistor 418 connects the positive terminal of voltage source 414 to conductor 10 "upstream" from region 14. In the particular circuit illustrated in FIGURE 4a, voltage source 414 cannot be connected directly to the  
15 conductor 10 without some resistance in the circuit, because large currents would be likely to flow in the resulting circuit, possibly damaging the conductor 10, the voltage source 414, or at least potentially increasing the  
20 magnetic field within region 14 to a point at which the magnetic sensing device 10 becomes nonlinear. Thus, in the circuit of FIGURE 4a, the resistors 416 and 418 serve dual functions, namely isolation of the voltage source from the  
25 circuit to which conductor 10 is connected, and also converting the voltage source 414 into a current source designated as 412. In operation of the circuit of FIGURE 4a, the test current  $I_{test}$  flows around the circuit including voltage  
30 source 414, resistor 418, conductor 10 in region 14, and resistor 416. The subject current  $I_{subject}$  to be measured flows through

conductor 10 as a result of a source circuit  
(not illustrated). In region 14 in which  
sensor 20 interacts with the planar magnetic  
field, the subject current  $I_{\text{subject}}$  and the test  
5 current  $I_{\text{test}}$  either add or subtract, depending  
upon their relative polarities. With the  
current directions indicated by the arrows in  
FIGURE 4, the currents add. Thus, the current  
generating the magnetic field within region 14  
10 is the vector sum (the "sum") of the subject  
current and the test current.

The term "current source" sometimes  
connotes an electrical source having a high  
impedance, so that variations in the load do  
15 not affect the current. Such a use of the term  
"current source" makes it equivalent to the  
term "constant-current source." Such circuits  
exist and use feedback principles to tend to  
maintain a given value of current, and in  
20 principle such a source will produce any  
voltage which may be required in order to make  
the design current flow. In actual practice,  
of course, these circuits have limits on the  
amount of voltage which can be generated, and  
25 so in the limit the constancy of the current  
fails. FIGURE 4b illustrates a current-sensing  
arrangement 400' including a circuit similar to  
that of FIGURE 4a, in which a constant-current  
source 414' is connected as a test current  
30 source. Constant-current source 414' of FIGURE  
4a has its terminals connected to conductor 10  
on either side (meaning on both sides) of

region 14, as was the case in FIGURE 4a. The difference between FIGURES 4a and 4b lies in the fact that the test current source in FIGURE 4b is a "current" source having, in principle, a high internal impedance. The high impedance prevents any voltage which may occur across its terminals from affecting the constancy of the current. Thus, it would appear to be superior to the arrangement of FIGURE 4a. However, the apparent simplicity of the arrangement of FIGURE 4b may not be realized in practice, since the constant-current source 414' is actually itself a circuit, which has components which must be protected from harmful surges and noise. Thus, in practice the arrangement of FIGURE 4 may require resistors similar to those of FIGURE 4a simply for protection of the constant-current source, or alternatively to provide a convenient test location for determining the existence of current flow. Regardless of whether a voltage source with resistors or a high-impedance constant-current source is used, the magnitude of the test current will be known. In the case of a voltage source with resistors, the current I will be equal to the voltage E divided by resistance R, so that  $I=E/R$  as known in the art, and in the case of a high-impedance current source the test current will be the design current.

According to a further hypostasis of the invention, a gating or control arrangement



is provided, which gates the test current source 410 on a recurrent basis, which is to say from time to time. The recurrence may be periodic or nonperiodic, but periodic systems  
5 are well known and simple to make, and so may be preferred. The test current is recurrently gated ON and OFF. As a result, the test current will be summed with the subject or unknown current flowing in conductor 10 to  
10 produce a magnetic field in region 14 which includes components attributable to the subject current and the test current. As the test current is gated ON and OFF, the net current producing the relevant magnetic field will  
15 change by an amount representative of the test current. If the test current sums with the subject current additively, as illustrated in FIGURES 4a and 4b, the magnetic field experienced by magnetic sensing device 20 will  
20 increase during those intervals in which the test current source is ON.

FIGURE 5a is a simplified diagram in block and schematic form illustrating another avatar of the invention. In FIGURE 5a,  
25 elements corresponding to those of FIGURE 4a are designated by like reference numerals. In FIGURE 5a, the current sensor arrangement 500 includes a source 510, which includes voltage source 414 and resistors 416 and 418. In  
30 addition, test current source 510 includes a switch 512 illustrated as a mechanical switch in accordance with conventions of the art.

There are other conventions which might be used, but the one selected is suitable for explanatory purposes. Those skilled in the art know that mechanical switches or relays are  
5 seldom used, as solid-state devices are often sufficient. Switch 512 is connected in-circuit with the test current source, so that the test current path is broken when the switch 512 is open or non-conductive. When the test current  
10 path is opened or broken, the test current ceases.

Switch 512 of current sensor arrangement 500 of FIGURE 5a is controlled, according to this other aspect of the  
15 invention, by a control circuit 514, which also receives sensed voltage from magnetic sensing device 20 by way of a path illustrated as a conductor 516. It is advantageous for control circuit 514 to control switch 512, because the  
20 fact of control provides control circuit 514 with some of the information it needs in order to determine the subject current, namely the times when the test current is ON and those in which it is OFF. In the absence of control of  
25 switch 512 by control circuit 514, the switch 512 would have to be controlled by some other entity. In that case, control circuit 514 could communicate with the control entity or with the switch itself to determine the switch  
30 state, or the control circuit could attempt fancy processing akin to correlation to attempt to determine the test and non-test intervals.

However, assuming that control circuit 514  
"knows" the state of switch 512 and the  
magnitude of the test current, it is in a  
position to determine the magnitude of the  
5 subject current.

FIGURE 5b illustrates as an  
alternative embodiment a current sensor  
arrangement 500', in which a high-impedance  
test current source is controlled, over a path  
10 566, by a control circuit 514'. Since, in  
principle, the current source will produce any  
voltage, however high, in order to cause the  
current to flow, it is not possible to open the  
test current circuit by means of a switch as in  
15 FIGURE 5a. Instead, the high-impedance  
constant-current source 414' is recurrently  
gated ON and OFF by a control signal applied to  
a gating input port 414'i.

FIGURE 6a illustrates a scheme for  
20 generating the test magnetic field component in  
region 14 by passing the test current  $I_{test}$  from  
a test current generator 612 through a  
conductor 610 which parallels conductor 10 in  
region 14. Conductor 610 is electrically or  
25 galvanically isolated from conductor 10. Such  
an arrangement is desirable for aiding in  
maintaining a relatively low-energy test  
circuit from a conductor 10 subject to high  
energy, in order to aid in protecting the  
30 components of the test current generator 612.  
So long as the configuration of the test  
current conductor generates the desired

magnetic field in the vicinity of magnetic sensing device 20, there should be no difference in the magnetic sensing device performance relative to the arrangements of  
5 FIGURES 2a, 2b, 4a, 4b, 5a, and 5b.

FIGURE 6b illustrates one physical configuration of the juxtaposed conductors which should be satisfactory. In FIGURE 6b, both conductors 10 and 610 have the same  
10 generally flat configuration, and they lie adjacent each other with their flat sides juxtaposed, separated only by a sheet <sup>630</sup>620 of dielectric insulation. In FIGURE 6b, the magnetic sensing device is illustrated as a  
15 flat rectangle 620, having its plane parallel to that of the generally planar conductors 10 and 610. However, if the magnetic sensing device 620 is sufficiently small relative to the other structures, the terms "lateral" and  
20 "orthogonal" become less important, as the sensor can simply be repositioned to sense the magnetic field.

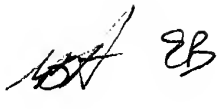


FIGURE 7a is a simplified perspective or isometric view of a printed-circuit board embodiment of an aspect of the invention, which  
25 uses flux concentrators in the region of the magnetic sensing device, and FIGURE 7b is a cross-section thereof in the region of the magnetic sensing device. In FIGURE 7a and 7b,  
30  $I_{\text{subject}}$  flows in elongated flat or planar conductor 10, which lies on the upper surface 790 of a dielectric slab or plate 790. The

integrated-circuit magnetic sensing device is designated as 720, and lies against the lower surface 790ls of the dielectric plate 790. In this embodiment, the magnetic sensing device is  
5 a lateral device, subject to the proviso that if it is small, the type is essentially irrelevant. A pair of generally flat magnetically permeable flux concentrator plates 792, 794 lie against the lower surface 790ls of  
10 the dielectric plate, with their planes aligned with the plane of the magnetic sensing device 720. The flux concentrator plates may be viewed as "scavenging" magnetic field lines which would tend to bypass the magnetic sensing  
15 device 720, or flowing through the sensor element at an undesirable angle, and causing those field lines to tend to pass through the sensor parallel with the plane of the sensor, thereby tending to increase the sensitivity of  
20 the sensor in the application.

Printed-circuit embodiments of the invention are very desirable, because the physical structure of the conductor 10 and test current conductors, if used, and their  
25 locations relative to each other and to the magnetic sensing device, can be controlled. Thus, experimentation can be used to determine the optimum locations of the various elements, so as to obtain the desired ratio of test flux  
30 to subject flux at the magnetic sensing device.

FIGURE 8 illustrates the relationship of the sensed voltage of a magnetic sensing device relative to the sum of the subject current and the test current for a particular physical layout. In FIGURE 8, the voltage  $V_{s1}$  results from a magnetic field resulting from an arbitrarily selected value of  $I_{subject}$ . For various values of  $I_{test}$  which cause a magnetic field component which sums with the magnetic field component caused by the subject current, the total sensed voltage rises along a line designated 810. Thus, at a test or bias current having a magnitude designated  $I_{test}$  in FIGURE 8 results in a sensed output voltage from the magnetic sensing device which is near  $V_{s2}$ , which represents an increase of  $\Delta V_s$  from the base value of  $V_{s1}$ . The sensitivity  $S$  of the magnetic field sensor device can then be expressed as:

$$S = \frac{V_{s2} - V_{s1}}{I_{subject} + I_{test} - I_{subject}} = \frac{\Delta V}{I_{test}} \quad 1$$

under all conditions of external and internal environment and noise.

In an embodiment of the invention for use in measuring alternating currents, the  
5 unipolar characteristic of some of the magnetic field sensor elements which can be used allows elimination of the absolute-value circuits which would otherwise be required. Those  
10 current sensor arrangements according to the various aspects of the invention which are made with printed-circuit or other bulk processing methods, as opposed to individual  
assembly/alignment of various elements, may provide both a cost advantage and the ability  
15 to maintain the dimensions of the various conductors, spacings, and magnetic relationships so that a very consistent current sensor arrangement can be fabricated from unit to unit. The processing of the data according  
20 to certain aspects of the invention allows use of devices which are inconsistent in performance from unit to unit and under various temperature or other conditions.

FIGURE 9 is a simplified diagram in  
25 block and schematic form, illustrating some details of a controller 514 of FIGURES 5a, 5b, or 6. In FIGURE 9, the magnetic-field-representative voltage produced by sensor 20 is applied by way of conductor set 516 to an  
30 amplifier or gain element 59 of control 514. The amplified signal is filtered in a filter 60 for noise reduction and applied to an analog-

to-digital converter (ADC) 61 for conversion into digital form. The digital signals representing the magnetic field are applied to microprocessor ( $\mu$ C) 65 including absolute-value and threshold calculations illustrated as 62. The microprocessor also includes information stored in memory, such as an EEPROM, which define the test current to be generated. The test current defining digital signals are applied by way of a path 68 to a digital-to-analog converter (DAC) 63 which generates an analog signal representing the test or calibration current. The analog signal is applied from DAC 63 to drive electronics, illustrated as a block 65, which generates the test current directly or which produces a control signal on conductor 566 for application to current source 414 of FIGURE 5b or test current generator 612 of FIGURE 6a.

Other embodiments of the invention will be apparent to those skilled in the art. For example, while the orientation of the plane and directions of maximum sensitivity of the magnetic field sensing device have been described as being preferably coincident with the plane and orientation in the plane of the magnetic field in the spatial region, this is only necessary if maximum sensitivity to the fields is desired; other orientations are possible, and may be advantageous when the magnetic fields are strong. Also, the test current excitation periods are easily



controlled by the microprocessor.

Thus, a current sensor arrangement (500, 500') for measuring a subject electrical current flow ( $I_{\text{subject}}$ ) includes an elongated conductor (10) having fixed dimensions, which is to say dimensions which are invariant with time. The elongated conductor (10) is configured for producing a generally planar magnetic field within a spatial region (14) adjacent the elongated conductor (10) when the subject electrical current ( $I_{\text{subject}}$ ) flows through the elongated conductor (10). A magnetic field sensing device (20) is located in the spatial region (14) with a preferred or particular direction or orientation generally parallel to the planar magnetic field. The magnetic field sensing device (20) produces a signal voltage (310) in response to a magnetic field in the particular direction therethrough, and the magnitude of the signal voltage (310) is approximately linearly related to the magnitude of the magnetic field in its vicinity, at least over a limited range of magnetic fields. The magnetic field sensing device (20) may be either temperature-dependent, variable in its sensitivity from device to device, or both, or neither. The magnetic field sensing device (20) produces a magnetic-field-representative signal voltage (310) in response to the magnetic field. The current sensor arrangement (500, 500') also includes a controllable test generator

magnetically coupled to the spatial region (14), for, when energized, generating a predetermined magnetic field component in the region (14). In some embodiments of the invention, the test generator is a current generator (410) which generates a predetermined current flow near or in the region (14) for generating a test magnetic field component in the spatial region (14). The test magnetic field component should be generally parallel with the planar magnetic field for maximum sensor sensitivity to the test component, whereby, or as a result of which, the magnetic field sensing device (20) produces a magnetic-field-representative signal voltage (350) related to the magnitude of the sum of the subject electric current ( $I_{\text{subject}}$ ) with the predetermined current ( $I_{\text{sense}}$ ). A control arrangement (514) is coupled to the magnetic field sensing device (20) and to the test generating means, for recurrently energizing (by way of switch 512 or gating port 414'i) the controllable test generating means, and for determining the magnitude of the subject current flow ( $I_{\text{subject}}$ ) in the elongated conductor (10) from at least (a) the magnitude of the magnetic-field-representative signal voltage during those times during which the controllable test generating means is energized, (b) the magnitude of the magnetic-field-representative signal voltage during times in which the controllable test current

generating means is not energized, and (c) the magnitude of the predetermined current.

In a particular manifestation of the invention, the recurrent energization is  
5 periodic. Among the magnetic field sensing devices (20) for which the invention is usable are giant magnetoresistive devices and spin-dependent tunneling devices. In one distinct version (400, 400', 500, 500') of the  
10 invention, the test generator is a test current generator (412) which is galvanically coupled to the elongated conductor (10) adjacent the spatial region (14), for causing the test current ( $I_{test}$ ) to flow through the elongated  
15 conductor (10) and thereby generate the test magnetic field component within the spatial region (14). In this distinct version, the control arrangement (514) comprises a switching arrangement (512 or gating signal), for, when  
20 in the conducting state, gating the predetermined test current to the elongated conductor (10), and for, when in the nonconducting state, preventing the predetermined current from flowing in the  
25 elongated conductor (10). The galvanic connections may be made by current conductors connected to the elongated conductor (10) on either side of the spatial region (14), and the current conductors may include resistors or  
30 resistance arrangements (416, 418).

In another distinct version of the current sensor arrangement (600) according to

the invention, the controllable test current generator comprises a second electrical conductor (610) extending through the spatial region (14), electrically isolated from the  
5 elongated conductor (10), and preferably parallel therewith. In this other distinct version, the control arrangement (614) includes a switching arrangement, for, when in the conducting state, gating the predetermined  
10 current to the second electrical conductor, and for, when in the nonconducting state, preventing the predetermined test current from flowing in the second electrical conductor.